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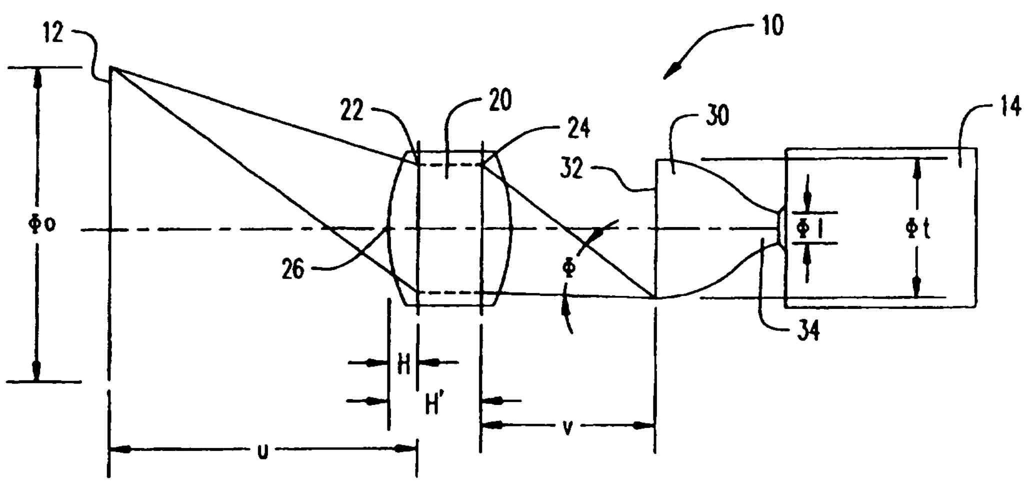

(57) Abstract

There is provided an optical imaging system (10) for generating imaging information from incoming radiation that has passed through a particular object. The optical imaging system (10) includes scintillating screen (12) for converting the incoming radiation to visible light, an image intensifier (14) for increasing the intensity of the visible light and a lens and taper combination (20, 30) for coupling the scintillating screen (12) to the image intensifier (14). The lens and taper combination (20, 30) has a fiber optic taper (30) for forming a viewable image based on the visible light and a lens (20) for directing the visible light to the fiber optic taper (30). Further, the optical imaging system (10) includes an output system for presenting the viewable imaging for clinical analysis.

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OPTICAL IMAGING SYSTEM

BACKGROUND OF THE INVENTION

I. Field of the Invention

The present invention relates generally to optical imaging systems for converting radiation, such as x-rays or gamma-rays, to visible light. More particularly, the present invention relates to a high quality diagnostic fluoroscopic imaging system having high photocollection efficiency with a low level of radiation exposure to the subject.

Optical imaging systems for medical diagnoses typically use radiation technologies, such as x-rays and gamma-rays. Such optical imaging systems are often used for extremity imaging in orthopedic, podiatry and sports medicine. For example, a typical optical imaging system may transmit x-rays through a body part, such as a patient's hand, and generate a video or printed image of the body part for analysis.

One concern with radiation-based optical imaging systems is the possible damage to the body part due to the radiation's high intensity flux. Existing optical imaging systems require large dosages of high intensity flux to achieve images that are acceptable for analysis. However, such large dosages of radiation may cause problems to the health of the patient, as well as the environment. Moreover, there is a need for an imaging system that is efficient, for example light in weight, less bulky and, thus, conducive to a portable imaging system.

One optical imaging system is a fluoroscopic x-ray imaging system that has microchannel plate image intensifiers. Such an x-ray imaging system employs a

phosphor screen for converting x-rays to visible light, a light intensifier for amplifying the visible light and an optical coupling to direct the visible light from the phosphor screen to the light intensifier. The optical coupling affects the intensity of the x-ray beam required to generate a quality image. Accordingly, a patient would be exposed to less x-ray radiation in an x-ray imaging system that has an efficient optical coupling. Thus, it is clearly desirable for an optical imaging system to have an efficient optical coupling, and thus improved photon collection efficiency.

Modern conventional medical image intensifiers use electron optics and, thus, provide excellent radiation performance. The present invention provides such excellent radiation performance in a smaller, less expensive and lower weight package.

II. Description of the Prior Art

The most difficult aspects of any imaging system is the collection of the visible light generated at the phosphor screen and coupling the phosphor screen to the image intensifier. For existing imaging systems, either a lens or a group of fiber optics are used to couple the phosphor screen to the image intensifier. For example, U.S. Patent No. 4,142,101 to L.I. Yin, which issued on February 27, 1979, titled LOW INTENSITY X-RAY AND GAMMA-RAY IMAGING DEVICE, provides an optical imaging device that operates at low doses of radiation. The optical imaging device includes a phosphor screen for converting radiation-to-visible light and a visible light intensifier coupled to the phosphor screen by a fiber optic plate. The visible light intensifier includes a photocathode for converting the visible light to electrons, a micro-channel plate amplifier for amplifying the electrons and an output phosphor for

converting the amplified electrons back to visible light. This patent uses a fiber optic plate to couple the phosphor screen to the visible light intensifier, and provides no recognition of the need for efficient optical coupling.

Lenses gather a very small fraction of the light generated at the phosphor screen due to the physical limitations imposed by the lens aperture and the lens-to-object distance necessary for image formation. Photometric calculations show that approximately 0.75% of the light photons generated at the phosphor screen will be collected by a f/1 lens and focused on an image intensifier with a 25 mm input diameter. With an 18 mm intensifier, the corresponding percentage would fall to 0.41%.

Fiber optics have a greater photon collection efficiency than lenses. However, only the core glass of the fiber optics conducts light while light falling on the sheath of the fiber optics and the extra-mural absorber are lost. Calculations based on formulae presented by Walter E. Sigmund in Fiber Optic Tapers in Electronic Imaging, (Electronic Imaging West, Pasadena, CA; April, 1989) indicate that 0.78% of the photons generated will be delivered to a 25 mm intensifier by a tapered fiber optic bundle, but that this would fall to 0.40% with an 18 mm intensifier. The overall collection efficiency of a taper is not better than an f/1 lens.

Accordingly, existing imaging systems, including the optical system described in the above cited U.S. Patent No. 4,142,101, do not provide an efficient optical coupling.

In addition, improvements in photocollection efficiency should also result in improvements in image brightness. While the photocollection efficiency described above is the true measure of optical system efficiency, the image intensifier reacts to input image brightness and a brightness gain results from the fact that the image is

minified. For the above systems with either 25 or 18 mm intensifiers, an f/1.0 lens will produce an image luminance approximately equal to 25% of the object brightness and a fiber optic taper will produce an image luminance of approximately 75%.

Generally, lenses and fiber optics have the following characteristics. When the object size is very large, the use of fiber optics is not practical for reasons of cost and practicality. A large fiber optic, such as one having a 215 mm input diameter, has not yet been manufactured and, if undertaken, would be cost prohibitive. Also, when the taper ratio, i.e. input diameter vs. outer diameter, is large, the photocollection efficiency of the fiber optic is no better than a conventional lens. In addition, fiber optics are only effective at transmitting light when the angle of incidence of the light is less than the numerical aperture of the fiber.

The present invention is an optical imaging system that includes a combination of a lens and fiber optics to obtain a significant improvement in optical or photon collection efficiency over existing systems which have either a simple lens or a group of fiber optics. The optical imaging system components are a phosphor screen, an image intensifier, and means for coupling the phosphor screen to the image intensifier. The phosphor screen converts x-ray radiation to visible light, and the image intensifier may operate in a magnetic field environment. In addition, the optical imaging system may include an output device to display or print the information converted by the phosphor screen and amplified by the image intensifier.

SUMMARY OF THE INVENTION

Against the foregoing background, it is a primary object of the present invention to provide an optical imaging system that includes a converter for converting radiation to visible light and means for efficiently collecting the visible light and directing it to an intensifier that has a high collection efficiency.

It is another object of the present invention to provide such an optical imaging system in which a combination of a lens and fiber optics is used to collect the visible light and direct the visible light to an intensifier having a lens with a very low F number.

It is a further object of the present invention to provide such an optical imaging system that generates diagnostic quality images and uses intensifiers that are not susceptible to magnetic fields.

It is yet another object of the present invention to provide such an optical imaging system that is not bulky, lightweight, and relatively inexpensive.

It is a still further object of the present invention to provide such an optical imaging system that is portable.

It is a yet further object of the present invention to provide such an optical imaging system that includes a zoom feature for adjusting the position of the lens relative to the fiber optics.

It is still yet a further object of the present invention to provide such an optical imaging system in a medical device for x-ray imaging of body parts.

To accomplish the foregoing objects and advantages, the present invention, in brief summary, is an optical imaging system for generating imaging information from incoming radiation that has passed through a particular object. The system comprises means for converting the incoming radiation to visible light, an image intensifier for

increasing the intensity of the visible light, and means for coupling the converting means to the image intensifier. The coupling means includes a fiber optic taper for forming a viewable image based on the visible light and a lens for directing the visible light to the fiber optic taper. In addition, the optical imaging system includes an output system for presenting the viewable image for clinical analysis.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and still further the objects and advantages of the present invention will be more apparent from the following detailed explanation of the preferred embodiments of the invention in connection with the accompanying drawings:

Fig. 1 is a diagrammatic view representing first and second preferred embodiments of the present invention;

Fig. 2 is a diagrammatic view of transmitted light losses that may occur in the fiber optic taper of Fig. 1;

Fig. 3 is a graph of a test analysis of taper input size based on varying screen sizes for a typical 50 mm lens design;

Fig. 4 is a graph of a test analysis of a hypothetical 75 mm lens that was scaled from the 50 mm lens design of Fig. 3;

Fig. 5 is a diagrammatic view of illumination by an object of the lens of Fig. 1;

Fig. 6 is another diagrammatic view of illumination by an object of the lens of Fig. 1;

Fig. 7 is a graph showing image luminance of the present invention of a 100 mm object; and

Fig. 8 is a graph showing image luminance of the present invention for a 150 mm object.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is an optical imaging system including a combination of a lens and fiber optics or fiber optic tapers to provide efficient photocollection or photon collection efficiency. Preferably, the optical imaging system is used in a fluoroscopic x-ray device for measuring extremities of the human body, such as a mini C-arm x-ray device. Although the preferred embodiments, described below, are directed to mini C-arm x-ray devices, it is to be understood that the present invention has application to a wide variety of optical imaging systems. For example, in addition to providing smaller size and cost advantages for mini C-arm type devices, the present invention provides economic cost advantages for larger x-ray devices as well.

The photon collection efficiency of a lens having a fixed size and focal length is a function of the minification required of the lens. Accordingly, the greater the minification, the less the photon collection efficiency. Also, fiber optic tapers are effective at transmitting light when the sine of the angle of incidence of the light is less than the numerical aperture of the fiber. Therefore, the fiber optic taper is used in conjunction with a lens to reduce the amount of minification required and, hence, improve the photon collection efficiency of the lens. At the same time, the transmission properties of the fiber optic are maintained by ensuring that the sine of the angle of the rays of light impinging on the fiber optic is at an angle less than or equal to the numerical aperture of the fiber.

Referring to the drawings and, in particular, to Fig. 1, there is provided an optical imaging system of the preferred embodiment which is generally represented by reference numeral 10. A scintillating or phosphor screen 12 is positioned at one end of the system 10 and an image intensifier 14 is positioned at the other end. The optical imaging system 10 combines a lens 20 and a fiber optic taper 30 that together form a coupling means between the phosphor screen 12 and the image intensifier 14. The fiber optic taper 30 has a conical type shape with a large diameter end 32 positioned adjacent the lens 20, and a smaller diameter end 34. Accordingly, the components of the optical imaging system, from left to right, are the phosphor screen 12, the lens 20, the fiber optic taper 30 and the image intensifier 14. In a preferred embodiment, the phosphor screen 12 is made of gadoliniumoxysulphide, terbium doped, more commonly referred to as a rare earth phosphor.

For operation of the optical image system 10, radiation from an energy source is transmitted through an object, such as a portion of a person's body, and received by the phosphor screen 12. The phosphor screen 12 is a conversion means for converting the radiation into visible light that is directed to the lens 20. The lens 20 forms an image of the object at the large end 32, which is shown as a viewed image at a small end 34 of the fiber optic taper. The visible light entering the lens 20 is refracted at a first principal plane 22, and the visible light exiting the lens is, again, refracted at second principal plane 24. For the present invention, the location of the second principal plane 24 is positioned as far back as possible from the front vertex 26 of the lens 20.

Various dimensions of the present invention are given in Fig. 1. ϕ_0 represents the diameter of the phosphor screen 12, and u is the distance from the phosphor screen 12 to the first principal plane 22 of the lens 20. H is the distance from a front vertex 26 of the lens 20 to the first principal plane 22, H' is the distance from the front vertex to the second principal plane 24, v is the distance from the second principal plane 24 to the large end 32 of the fiber optic taper 30, ϕ_t is the diameter of the large end 32, and ϕ_i is the diameter of the small end 34.

When the fiber optic taper 30 is interposed between the lens 20 and the image, then the minification required of the lens is substantially reduced. Also, the collection efficiency increases as the square of this reduction and the image brightness correspondingly improves. As the size of the image, for an object of fixed size, is increased, the lens is moved closer to the object and, hence, subtends a larger angle with respect to any point on the image. Thus, there is an increase in the photon collection efficiency. The degree of improvement obtained by this technique is limited when the sine of the angle of the most oblique ray entering the fiber optic taper 30 exceeds the numerical aperture of the fiber optic taper, the visible light will not be transmitted to the image intensifier 14. This is not a sharp cut-off, but is rather a dimming of the image at its edges in which the center brightness is enhanced.

The focal length of the lens is dictated by the screen size. For the present invention, the focal length ranges from about 25 mm to about 125 mm and, preferably, the focal length is from about 50 mm to about 80 mm. As described below, the focal lengths for the first and second preferred embodiments are 50 mm and 58 mm, respectively.

the focal length is from about 50 mm to about 80 mm. As described below, the focal lengths for the first and second preferred embodiments are 50 mm and 58 mm, respectively.

The first preferred embodiment of the present invention is a system design having the following primary parameters that would provide both 100 and 150 mm field of views in a single intensifier assembly:

TABLE 1: 100/150 mm System

Screen Diameter (mm)	100	150
Taper Diameter (mm)	42	42
II Diameter (mm)	17.5	17.5
Lens - Focal Length (mm)	50	50
- f/number	1.2	1.2
Field of View (degrees)	47.7	47.0
Relative Brightness - Center	0.758	0.749
- 80% of radius	0.505	0.440
- Outer Edge	0.364	0.312
Object to Lens Distance (mm)	113	172
(inches)	4.45	6.77
Lens to Image Distance (Includes taper and image intensifier) (mm)	58	51
(inches)	2.28	2.10
Overall Image Chain Length (mm) [includes taper and image intensifier]	290	342
(inches)	11.42	13.46

The second preferred embodiment of the present invention is another system design having the following primary parameters that would provide 150 and 230 mm field of views in a single intensifier assembly:

TABLE 2: 150/230 mm System

Screen Diameter (mm)	150	230
Taper Diameter (mm)	44	44
II Diameter (mm)	17.5	17.5
Lens - Focal Length (mm)	58	58
- f/number	1.2	1.2
Field of View (degrees)	40.4	40.8
Relative Brightness - Center	0.722	0.745
- 80% of radius	0.464	0.430
- Outer Edge	0.349	0.319
Object to Lens Distance (mm)	204	309
(inches)	8.03	12.16
Lens to Image Distance		

(Includes taper and image intensifier)	(mm)	55	49
	(inches)	2.16	1.93
Overall Image Chain Length [includes taper and image intensifier]	(mm)	383	483
	(inches)	15.08	19.02

In addition, the first and second preferred embodiments includes the following properties for the fiber optic taper 30:

TABLE 3: Properties for the Fiber Optic Taper

SPECIFICATION	DESCRIPTION			
Glass Type	SFO 32A			
Large O.D. Fiber Size	25 µm or less			
Minimum Clear Apertures	50 mm to 25 mm			
Gross Distortion	< 5%			
Shear Distortion	< 0.004			
Magnification Tolerance	2.00 ± 0.11			
O.D. Large End	53 mm + 0.0 mm/ - 0.13 mm			
O.D. Small End	26.5 mm (ref.)			
Length of Taper	43.5 mm ± 0.5 mm			
Image Alignment	0.020 TIR maximum			
Optical Finish	10 fringes or better - 20/10 scr/dig			
Radioactive Material	< 500 ppm Thorium Oxide			
Numerical Aperture	1.0 at Small End			
Chickenwire (CW)	Width of continuous CW shall not exceed 2 fibers. CW greater than 2 fibers wide will be treated as a blemish (length/width).			
	<u>SIZE</u>	ZONE 1 <u>25 MM (DIA.)</u>	ZONE 2 <u>25-40 MM</u>	ZONE 3 <u>40-50 MM</u>
	< 0.070	disregard	disregard	disregard
	0.070-0.140	3	5	6
	0.140-0.200	2	3	4
	0.200-0.250	1	2	3
	> 0.250	0	0	1
Blemishes	<u>SIZE</u>		<u>ALLOWED</u>	
	0.010"		none	
	0.006"-0.010"		10	
	0.003"-0.006"		30	
	0.001"-0.003"		40	
Other	All other specifications as per Schott FP87-1 standard taper specification.			

In another embodiment that has been tested, the field of view was 215 mm with a 56 mm custom f/1.02 lens designed and built by Optics for Research Inc. The embodiment included a 36 mm fiber optic taper and a 17.5 mm, proximity focused, microchannel plate image intensifier.

For the present invention, the F number ranges from about 1.0 to about 5.6. More preferably, lenses having an F number from about 1.0 to about 1.2 are desired to maintain low levels of intensity and, thus, minimize the intensity of the x-ray beam. At this time, the lowest available F number with proper field of view is about 1.0. It is envisioned that a smaller F number is better, provided we get a field of view, however a smaller F number is not commercially available.

Referring to Fig. 2, additional losses may be incurred in the fiber optic taper 30, namely losses within the numerical aperture of the fiber and transmission and cladding fraction losses. The transmission loss of the core 36 of a typical fiber optic taper is only 2% per inch of length. The primary loss in any fused fiber optic results from the light being only transmitted by the core 36. In other words, light is not transmitted by the cladding 38 or extra mural absorbers (EMA), such as black glass, incorporated into the fiber optic taper 30. EMA captures light that escapes from the fibers because it is outside of the numerical aperture and if not captured would reduce image contrast and resolution.

For the preferred embodiments, shown in the above table, not all of the light is contained within the numerical aperture. This condition depends on the final selection of taper input size. The taper input size is as large as possible in order to have optimal optical performance. For example, a 250 mm system with a 75 mm lens has an image

brightness that is about 36% greater than that of a 150 mm system with a 50 mm lens. The taper input size is limited by undesirable effects created by vignetting in the lens and variation of luminance over the diameter of the image. Thus, as the size of the taper input is increased, the field of view of the lens is exceeded and the edges become dimmer.

Referring to Fig. 3, for the preferred embodiment, a test analysis was performed on a 50 mm lens made by Nikon for its 35 mm SLR cameras in which limits have been applied based on the above vignetting effects and luminance variations. The field of view was limited to 46 degrees and the ratio of center to edge luminance was limited to 2:1. Up to and including 100 mm screen sizes, the system was limited by the ratio of center-to-edge brightness; beyond that point, it was limited by field of view. Since the taper size varies only slightly between certain screen size ranges, such as from about 100 mm to about 150 mm, a zoom feature may also be incorporated into the present invention.

Referring to Fig. 4, the lenses of the present invention may be virtually any size by simply scaling an existing design, such as the above 50 mm lens shown in Fig. 3. Fig. 4 shows the same analysis as above for the 50 mm lens in which a hypothetical 75 mm lens is scaled from the 50 mm lens design. In this case, the taper size is limited by center-to-edge brightness considerations throughout the screen size range. Although the taper size varies much more throughout the entire size range, the variation between reasonable zoom increments, such as from about 100 mm to about 150 mm, is not large and is still reasonable to build dual image size systems.

Thus, there is no fundamental limit to the screen size of the image intensifier of the present invention, such as a 500 mm intensifier or larger, since all components including the lens, fiber taper and microchannel plate intensifier, can be scaled to larger sizes. Although larger fiber optic tapers tend to be expensive, such costs generally become more reasonable in time with advances in technology and mass production. In addition, the cost of building a scaled image intensifier screen is much less than the cost of building large conventional intensifiers in vacuum envelopes, particularly medical intensifiers.

In an alternative embodiment, not all light can be contained within the numerical aperture but EMA would be needed and there would be brightness trailoff. Also, light would escape between fibers resulting in a loss of contrast. Hence, the additional losses result from the fraction of the cladding 38 so that the estimated total transmittance of the fiber optic taper 30 will be at least 0.75.

Concerning the effects created by variation of luminance over the diameter of the image, the present system may include a filter for shaping the x-ray beam intensity across the diameter of the image to compensate for non-uniform gain across the image. The filter preferably has a cone-like shape in which the thickest portion is in the center and the thinnest portion is at the edges. The filter is inserted into the x-ray beam to counterbalance the above variation in image illuminance.

In addition, the present system may include a proximity focused microchannel plate intensifier that has a uniform gain across its' diameter. Although not mandatory, such proximity focused intensifier may be used in applications where the presence of magnetic fields may distort the images.

Accordingly, the photometry of the lens and taper combination has been numerically analyzed. Thus, it is necessary to begin with an understanding of the flux of light from a small source. Kingslake's reference, Optical System Design by Rudolf Kingslake (Academic Press, 1983) provides that the flux of light from a small source is:

$$F = I\,\omega \qquad (1)$$

where F is the flux, I is the intensity of the source and ω is the solid angle in which the flux is measured.

Referring to Fig. 5, the lens 20 is illuminated by an object 16 at a distance of u - H from the front vertex 26 of the lens. Also, a small plane source of area A_0 and luminance B is in the plane of the object. For example, A_o corresponds to the area and B corresponds to the luminance of the phosphor screen 12. The lens 20 is divided into a series of concentric rings 40 and each ring is, in turn, divided into small segments or lens elements 42.

To determine the illuminance of the image at any point, it is necessary to integrate the illuminance, due to source A_0 , for each lens element 42. The distance between the lens element 42 and the source A_0 is d.

In a three dimensional Cartesian coordinate system, the source A_0 can be described as being located at x_1, y_1, z_1 and the lens element 42 at x_2, y_2, z_2. The center of the object 16 and lens elements 42 are at:

Object Element		Lens Element	
$x_1 = R$	(2a)	$X_2 = (r + \frac{\delta r}{2})\cos(\theta + \frac{\delta\theta}{2})$	(3a)

$$y_1 = 0 \tag{2b}$$

$$X_2 = (r + \frac{\delta r}{2}) \sin(\theta + \frac{\delta\theta}{2}) \tag{3b}$$

$$z_1 = u - H \tag{2c}$$

$$Z_2 = 0 \tag{3c}$$

The intensity of a plane source falls off at increasing angles of view, because of Lambert's cosine law of intensity. The angle of view of the small element in the object plane is the angle between the ray in question and a line perpendicular to the element. Space analytic geometry defines the angle between two lines as:

$$\cos(\alpha) = \frac{a_1 a_2 + b_1 b_2 + c_1 c_2}{\sqrt{[a_1^2 + b_1^2 + c_1^2]}\sqrt{[a_2^2 + b_2^2 + c_2^2]}} \tag{4}$$

where a_n:b_n:c_n are the direction of the line, defined as:

$$a_n = x_2 - x_1 \tag{5a}$$

$$b_n = y_2 - y_1 \tag{5b}$$

$$c_n = z_2 - z_1 \tag{5c}$$

where the subscript 1 refers to the intersection point, and the subscript 2 refers to the other end of the lines.

When one line is perpendicular to the object plane, equation (4) becomes:

$$\cos(\alpha') = \frac{c_1}{\sqrt{[a_1^2 + b_1^2 + c_1^2]}} \tag{6}$$

where α' denotes the angle to the midpoint of an element 42.

The intensity in the direction of the lens element 42 is:

$$I(\alpha') = A_0 B \cos(\alpha') \tag{7}$$

Referring to Fig. 6, the solid angle ω can be determined by calculating the angles between the lines that define how the finite lens element 42, at its' corners, subtends the source. δα is associated with δr, δB' is associated with δθ at r and δB" is associated with δθ at r + δr.

The finite element, that subtends the source, is approximately a trapezoid. The area of the trapezoid projected in the direction of the source is:

$$\delta A = \delta\alpha \frac{(\delta\beta' + \delta\beta'')}{2} d^2 \tag{8}$$

and the solid angle, ω, is:

$$\omega = \delta\alpha \frac{(\delta\beta' + \delta\beta'')}{2} \tag{9}$$

At the lens 20, the finite element is assumed to be a plane surface, and Lambert's cosine law of illuminance applies, introducing another cosine term. The incremental flux entering the lens 20 at each element 42 on the lens surface is:

$$\delta F = A_0 B \cos^2(\alpha')\, \delta\alpha \frac{(\delta\beta' + \delta\beta'')}{2} \tag{10}$$

The total flux of visible light entering the lens 20 is:

$$F_0 = \sum_{r=0}^{r=r_1} \sum_{\theta=0}^{\theta=2\pi} \delta F \tag{11}$$

where r_1 is the radius of the lens aperture. The flux of light falling on the image is equal to the flux of light entering the lens 20, except for transmittance losses in the

lens, and the fiber optic taper 30. The illuminance of the image, relative to Lambert brightness, is:

$$\frac{E_i}{\pi B} = \frac{T_l T_t F_0}{\pi A_i} \tag{12}$$

$$\frac{E_i}{\pi B} = \sum_{r=0}^{r=r_1} \sum_{\theta=0}^{\theta=2\pi} \frac{T_l T_t \cos^2(\alpha')}{2\pi m^2} \delta\alpha(\delta\beta' + \delta\beta'') \tag{13}$$

where m is the image magnification and $m^2 = A_i/A_0$.

Finally, the entrance angle of the light ray directed into the fiber optic is considered. This is done in the same manner that the angle of view between the lens element 42 and the source A_0 was calculated. The location of the image at the fiber optic taper 30 is defined by:

$$x_l = -mR \tag{15a}$$

$$y_l = 0 \tag{15b}$$

$$z_l = -v \tag{15c}$$

Equation (6) is used to calculate the entry angle, Y, in the fiber optic taper 30. For the ray to pass through the taper 30, the following condition must be met:

$$\sin(Y) \le \frac{\phi_i}{\phi_t} \tag{17}$$

The above equations are used to calculate the distribution of image brightness for 100 and 150 mm screen sizes. For the preferred embodiment, a computer program was used to facilitate these calculations by numerically dividing the lens 20 into 31,400 finite elements. Using the computer program, the brightness of an object

placed a far distance from the lens was calculated, a situation in which the simplifying assumptions usually made are valid. Kingslake shows that for a lens with 100% light transmission, the brightness of the image is:

$$\frac{E_i}{\pi B} = \frac{1}{4N^2} \tag{18}$$

where N is the f/number of the lens. For an f/1.2 lens, the above equation provides an image brightness result of 0.17361. In particular, the computer program calculated the centerline brightness of a large object placed 50 m from the lens, with an image magnification of 0.001, to be 0.17365. Thus, the computer program provides highly accurate results and support to the results presented. The above equation approximately describes the image brightness that is expected from a lens only system. As will be seen below, a typical system with a lens/taper combination will yield 4.3 times the image brightness of a lens only system and will equal the performance of a taper only system, but at a much lower cost, and with large image sizes.

The above equations have calculated the distribution of image brightness for 100 and 150 mm screen sizes. The results of the calculations give a center image brightness of about 15% greater than predicted by simple lens theory and an edge brightness about 50% less.

Figs. 7 and 8 show the results of the above described calculations. The image brightness is maintained at greater than 60% of its' central value over 80% of the image with a 42 mm taper. This results in a 45% improvement in central image brightness. Larger fiber optic tapers might be used, but then the field of view of the lens will be exceeded substantially and vignetting problems will occur. A small fringe

arising from the increase in taper size, is that the length of the assembly is reduced by just over 1 inch.

Optical bench measurements of relative brightness at the center of the image gave results approximately 30% less than predicted by the finite element analysis. This difference arises from the intrinsic errors involved in the finite element process or from the difficulties in making the measurement with currently available equipment. However, whether based on measurement or theory, it is clear that increased taper size leads to improve optical performance and, hence, lower x-ray to light conversion factors.

Thus, the present fluoroscopic x-ray imaging system, unlike any known system, found that the principal plane location should be as far back in the lens as possible. It achieves a much higher collection efficiency using light photon techniques in combination with fiber optic taper 30. Furthermore, the imaging system avoids magnetic shielding and its deleterious effects. It also results in a less bulky system that is, therefore, less in weight and less in cost. The less bulky, less in weight imaging system is, therefore, readily incorporated into a portable device.

The invention having been thus described with particular reference to the preferred forms thereof, it will be obvious that various changes and modifications may be made therein without departing from the spirit and scope of the invention as defined in the appended claims.

Wherefore, what is claimed is:

1. An optical imaging system for generating imaging information from incoming radiation that has passed through a particular object, said optical imaging system comprising:

means for converting the incoming radiation to visible light;

an image intensifier for intensifying the visible light,

means for coupling said converting means to said image intensifier, said coupling means including a fiber optic taper for forming a viewable image based on the visible light and a lens for directing the visible light to said fiber optic taper; and

an output system for presenting said viewable image for clinical analysis.

2. The optical imaging system of claim 1, wherein said fiber optic taper is physically and optically connected to said image intensifier.

3. The optical imaging system of claim 1, wherein said lens is positioned between said converting means and said image intensifier.

4. The optical imaging system of claim 1, wherein said lens includes a principal image plane and a principal object plane, and wherein said principal image plane is in front of said principal object plane.

5. The optical imaging system of claim 1, wherein said converting means is a scintillating screen.

6. The optical imaging system of claim 5, wherein said scintillating screen comprises a rare earth phosphor.

7. The optical imaging system of claim 1, wherein said converting means has a screen diameter that is about 100 mm to about 215 mm.

8. The optical imaging system of claim 7, wherein said converting means has a screen diameter that is about 100 mm.

9. The optical imaging system of claim 7, wherein said converting means has a screen diameter that is about 150 mm.

10. The optical imaging system of claim 7, wherein said converting means is about 215 mm.

11. The optical imaging system of claim 1, wherein said fiber optic taper has a large end and a small end, and wherein said lens forms an image of the particular object at the large end and a viewed image at the small end.

12. The optical imaging system of claim 11, wherein the large end of said fiber optic taper is about 42 mm.

13. The optical imaging system of claim 11, wherein the small end of said fiber optic taper is about 17.5 mm.

14. The optical imaging system of claim 1, wherein a focal length of said lens is from about 25 mm to about 125 mm.

15. The optical imaging system of claim 14, wherein a focal length of said lens is from about 50 mm to about 80 mm.

16. The optical imaging system of claim 15, wherein the focal length of said lens is about 50 mm.

17. The optical imaging system of claim 15, wherein the focal length of said lens is about 58 mm.

18. The optical imaging system of claim 1, wherein said lens has an F number from about 1.0 to about 5.6.

19. The optical imaging system of claim 18, wherein the F number is greater than zero and up to about 5.6.

20. The optical imaging system of claim 19, wherein the F number is from about 1.0 to about 5.6.

21. The optical imaging system of claim 20, wherein the F number is from about 1.0 to about 1.2.

22. The optical imaging system of claim 1, wherein the optical imaging system is used in a fluoroscopic x-ray device.

23. The optical imaging system of claim 22, wherein the fluoroscopic x-ray device images extremities of a human body.

24. The optical imaging system of claim 22, wherein the fluoroscopic x-ray device is used in a mini C-arm X-ray device.

25. The optical imaging system of claim 1, further comprising means for filtering the illuminance of the visible light to compensate for non-uniform gain throughout a cross-section of the visible light.

AMENDED CLAIMS

[received by the International Bureau on 21 July 1997 (21.07.97);
original claims 18 cancelled;
original claims 1, 4, 10 and 19 amended;
remaining claims unchanged (4 pages)]

1. An optical imaging system for generating imaging information from incoming radiation that has passed through a particular object, said optical imaging system comprising:

means for converting the incoming radiation to visible light;

an image intensifier for intensifying the visible light;

means for coupling said converting means to said image intensifier, said coupling means including a fiber optic taper for forming a viewable image based on the visible light and a lens for directing the visible light to said fiber optic taper, wherein said lens includes a principal image plane and a principal object plane, said principal image plane being in front of said principal object plane; and

an output system for presenting said viewable image for clinical analysis.

2. The optical imaging system of claim 1, wherein said fiber optic taper is physically and optically connected to said image intensifier.

3. The optical imaging system of claim 1, wherein said lens is positioned between said converting means and said image intensifier.

4. The optical imaging system of claim 1, wherein said lens further comprises a front vertex, said second principal plane being positioned at the furthest possible distance from said front vertex.

5. The optical imaging system of claim 1, wherein said converting means is a scintillating screen.

6. The optical imaging system of claim 5, wherein said scintillating screen comprises a rare earth phosphor.

7. The optical imaging system of claim 1, wherein said converting means has a screen diameter that is about 100 mm to about 215 mm.

8. The optical imaging system of claim 7, wherein said converting means has a screen diameter that is about 100 mm.

9. The optical imaging system of claim 7, wherein said converting means has a screen diameter that is about 150 mm.

10. The optical imaging system of claim 7, wherein said converting means has a screen diameter that is about 215 mm.

AMENDED SHEET (ARTICLE 19)

11. The optical imaging system of claim 1, wherein said fiber optic taper has a large end and a small end, and wherein said lens forms an image of the particular object at the large end and a viewed image at the small end.

12. The optical imaging system of claim 11, wherein the large end of said fiber optic taper is about 42 mm.

13. The optical imaging system of claim 11, wherein the small end of said fiber optic taper is about 17.5 mm.

14. The optical imaging system of claim 1, wherein a focal length of said lens is from about 25 mm to about 125 mm.

15. The optical imaging system of claim 14, wherein a focal length of said lens is from about 50 mm to about 80 mm.

16. The optical imaging system of claim 15, wherein the focal length of said lens is about 50 mm.

17. The optical imaging system of claim 15, wherein the focal length of said lens is about 58 mm.

AMENDED SHEET (ARTICLE 19)

19. The optical imaging system of claim 1, wherein the F number is greater than zero and up to about 5.6.

20. The optical imaging system of claim 19, wherein the F number is from about 1.0 to about 5.6.

21. The optical imaging system of claim 20, wherein the F number is from about 1.0 to about 1.2.

22. The optical imaging system of claim 1, wherein the optical imaging system is used in a fluoroscopic x-ray device.

23. The optical imaging system of claim 22, wherein the fluoroscopic x-ray device images extremities of a human body.

24. The optical imaging system of claim 22, wherein the fluoroscopic x-ray device is used in a mini C-arm X-ray device.

25. The optical imaging system of claim 1, further comprising means for filtering the illuminance of the visible light to compensate for non-uniform gain throughout a cross-section of the visible light.

STATEMENT UNDER ARTICLE 19

This application now contains claims 1 through 17 and 19 through 25. Claim 1, 4, 10 and 19 have been amended. Claim 18 has been cancelled. Claims 2, 3, 5 through 9, 11 through 17, and 20 through 25 are unchanged.

Claim 10 has been amended to make clear that the converting means has a screen diameter that is about 215 mm. Also, claim 18 has been cancelled as it is a duplicate of dependent claim 20; and claim 19 which previously depended from claim 18 has been amended to depend from claim 1.

Claim 1 has also been amended to define further that the lens of the present invention includes a principal image plane and a principal object plane, and that the principal image plane is in front of the principal object plane. This aspect of the invention is supported by the original disclosure at page 8, lines 16 through 22 and page 9, lines 1 through 7.

Claim 4 has also been amended to recite that the lens further comprises a front vertex and that the second principal plane is positioned at the furthest possible distance from the front vertex. This aspect of the invention is also supported by the original disclosure at page 8, lines 16 through 22 and page 9, lines 1 through 7.

With respect to the above amended claims, it is clear that no new matter has been inserted into the application.

The search report cites as particularly relevant, considered alone, the following United States patent:

U.S. Patent No. 4,521,688 to Yin ("the Yin patent"), which issued on June 4, 1985, titled THREE-DIMENSIONAL TOMOGRAPHIC IMAGING DEVICE FOR X-RAY AND GAMMA-RAY EMITTING OBJECTS,, applied to claims 1 through 24 of the application; this patent was further considered relevant to the

examination of claim 25 of the application when considered in combination with the other cited patents.

The search report cites as particularly relevant, when combined with other documents, the following U.S. Patents:

U.S. Patent No. 3,755,672 to Edholm et al. ("the Edholm et al. patent"), which issued on August 28, 1972, titled EXPOSURE COMPENSATING DEVICE FOR RADIOGRAPHIC APPARATUS, applied to claim 25 of the application.

U.S. Patent No.3,665,191 to Moody ("the Moody patent"), which issued on May 23, 1972, titled FILTER FOR COMPENSATING EFFICIENCY DIFFERENCES IN AN OPTICAL SYSTEM, applied to claim 25 of the application.

Independent claim 1, as amended, provides an optical imaging system for generating information from incoming radiation that has passed through a particular object. The optical imaging system includes a converter that converts the incoming radiation to visible light and an image intensifier for intensifying the visible light. The converter is coupled to the image intensifier across a fiber optic taper for forming a viewable image based on the visible light and a lens for directing the visible light to the fiber optic taper. The lens includes a principal image

plane and a principal object plane. The principal image plane is in front of the principal object plane. The optical imaging system also includes an output system for presenting the viewable image for clinical analysis.

The purpose of the present invention is to provide an optical imaging system with significantly improved optical and photon collection efficiency over existing imaging systems, resulting in increased image brightness. The present invention also provides an imaging system that is less bulky, i.e., less weight and less cost, and, thus, can be readily incorporated into a portable device. The above features are accomplished by utilizing a lens (i.e., light photon techniques) and fiber optics combination in which the lens has a principal object plane located in front of the principal object plane.

The Yin patent is directed to a three dimensional and tomographic imaging device for X-ray and Gamma-ray emitting objects. The imaging device includes a multiple-pin hole aperture plate held spaced from an x-ray or gamma-ray to visible-light converter which is coupled to a visible-light intensifier. The spacing between the aperture plate and the converter is chosen such that the mini-images of an emitting object formed by the pinholes do not substantially overlap as they impinge on the converter. The output of the image

intensifier is digitized and directed to a digital computer for processing. The computer then displays a three-dimensional image of the object, based on the processed information.

The search report primarily focuses on column 5, lines 23 through 29 of the Yin patent which merely suggests that the converter may alternatively be coupled to the intensifier across a combination of a lens system and a fiber optics plate (tapered or not tapered). However, the Yin patent does not disclose the type of lens or the manner in which the lens and fiber optics plate are coupled between the converter and the intensifier. Unlike the present invention as recited in claim 1, the Yin patent does not disclose or suggest a lens including a principal image plane and a principal object plane and, moreover, the principal image plane being in front of the principal object plane.

Moreover, the Yin patent merely suggests that a lens system and fiber optics combination would allow for a converter of a different size than the intensifier input. The Yin patent does not teach or suggest how a lens and a fiber optic taper can be utilized in an imaging system to increase the brightness of the image, as provided in claim 1 of the present invention. The Yin patent also does not teach or suggest how a lens and fiber optic taper can be

employed to decrease the overall size and weight of the imaging system such that it can readily be incorporated into a portable device, as provided in claim 1 of the present invention. Accordingly, the subject matter disclosed in the Yin patent would neither teach nor suggest the invention of claim 1. The remaining patents cited, the Edholm et al. and Moody patents, are directed to a radiation filter and no combination thereof would suggest the present invention of claim 1.

Claims 2 through 17 and 19 through 25 depend from claim 1 and are distinguished from the cited art for the reasons stated above.

In addition, claims 7 through 17 and 19 through 21 recite particular configurations of the components of claim 1 to increase image brightness and to decrease the size and weight of the overall imaging system. Claims 7 through 10 recite a specific screen diameter for the converting means. Claims 11 through 13 recite the size and shape of the fiber optic taper. Claims 14 through 17 recite specific the focal length of the lens. Claims 19 through 21 recite the F number of the lens. As previously discussed, the Yin patent merely suggests a lens system and fiber optics combination to allow a different converter size than the intensifier input. It is important to understand that the mere

combination of a lens system and fiber optics system does not provide increased image brightness or even decreased size and weight of the overall imaging system, as provided in the above claims. Therefore, claims 7 through 10, 12 through 17 and 19 through 21 are further distinguished from the cited art.

In view of the foregoing, applicant respectfully submits that all claims presented in this application are patentably distinguishable over each cited patent and the cited combination of patents. Accordingly, applicant respectfully requests favorable consideration of the claims of the present application.

Due to the amendments to claims 1, 4, 10 and 19 and cancellation of claim 18, applicant is submitting herewith replacement pages 21 through 24 for the above application.

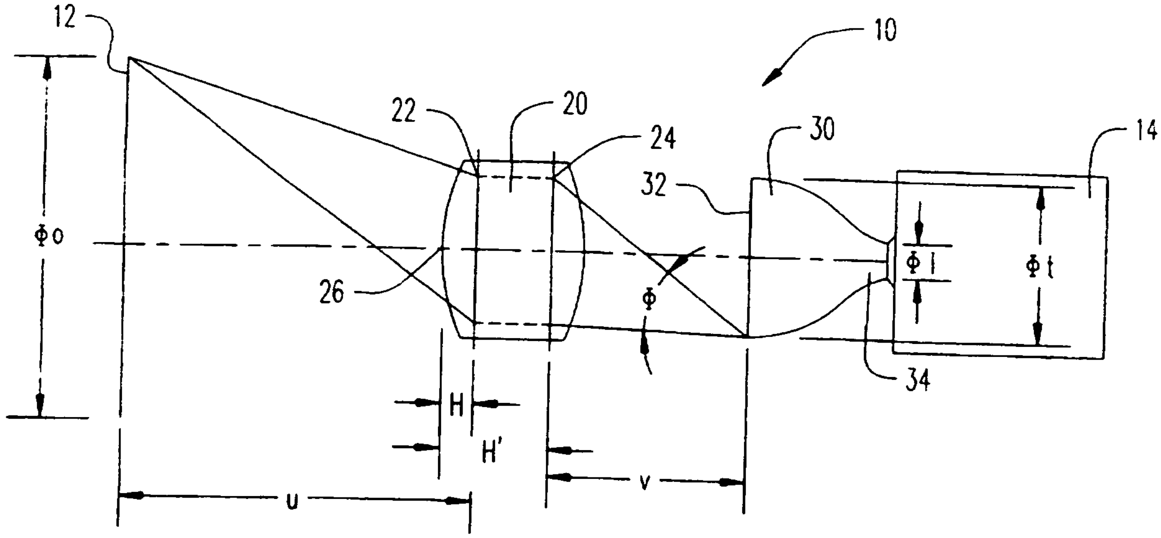

FIG. 1

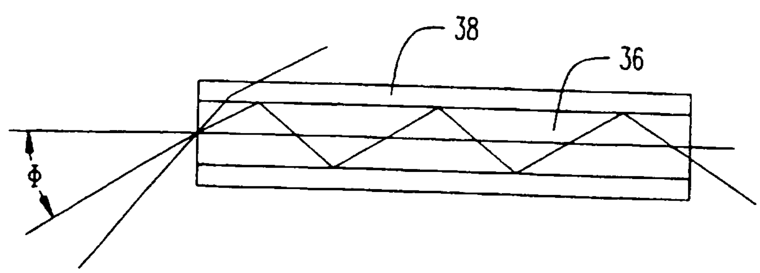

FIG. 2

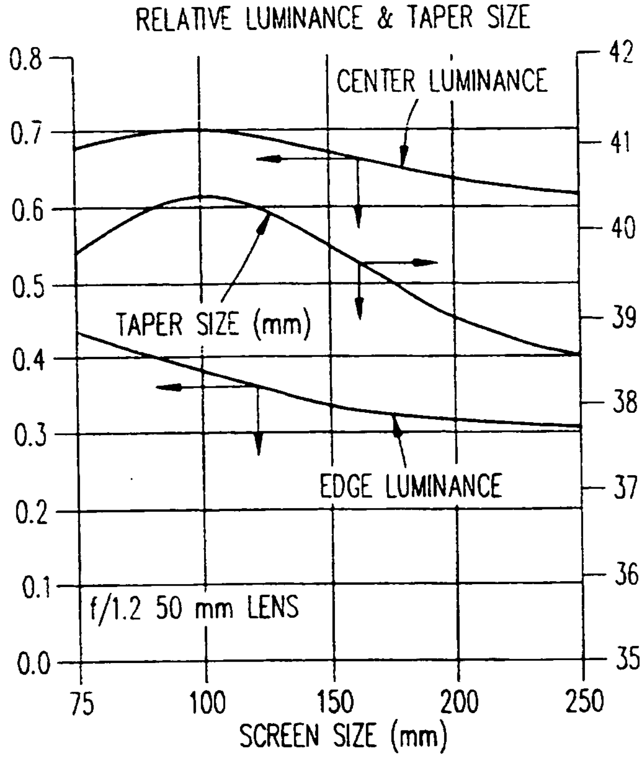

FIG. 3

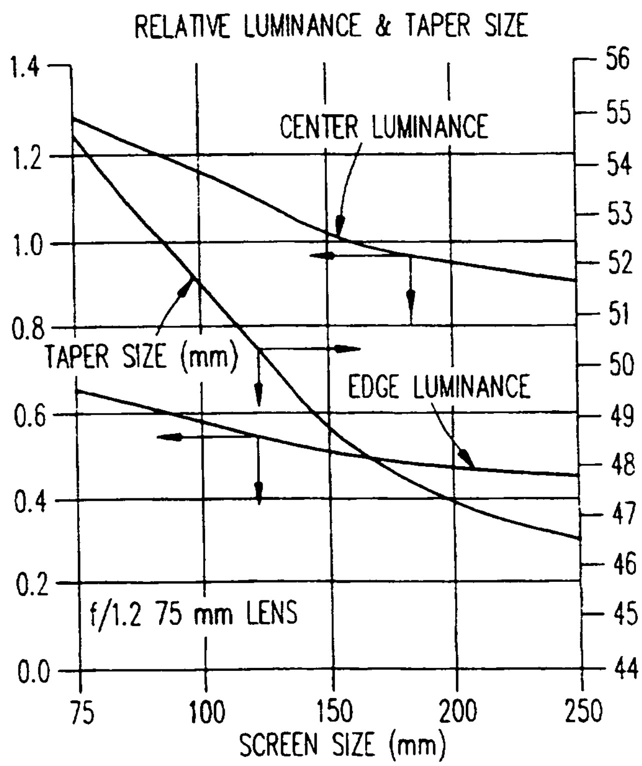

FIG. 4

SUBSTITUTE SHEET (RULE 26)

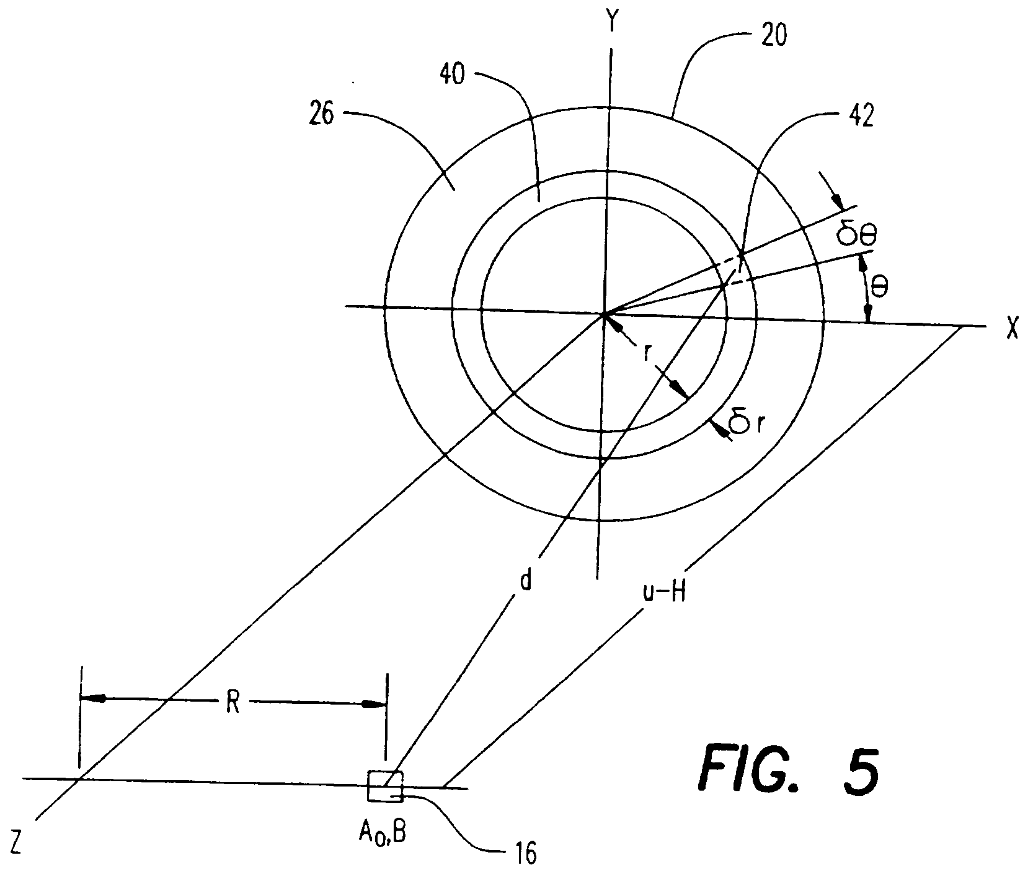

FIG. 5

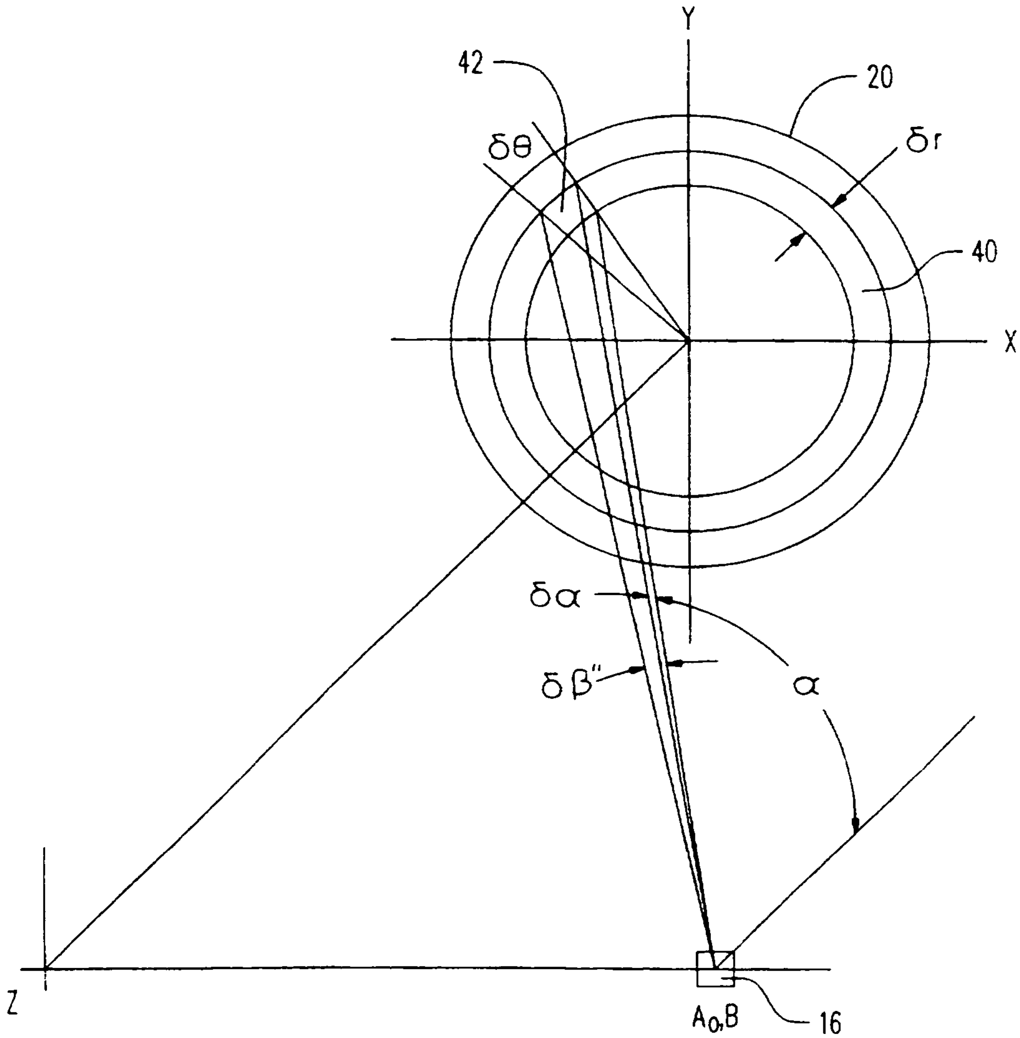

FIG. 6

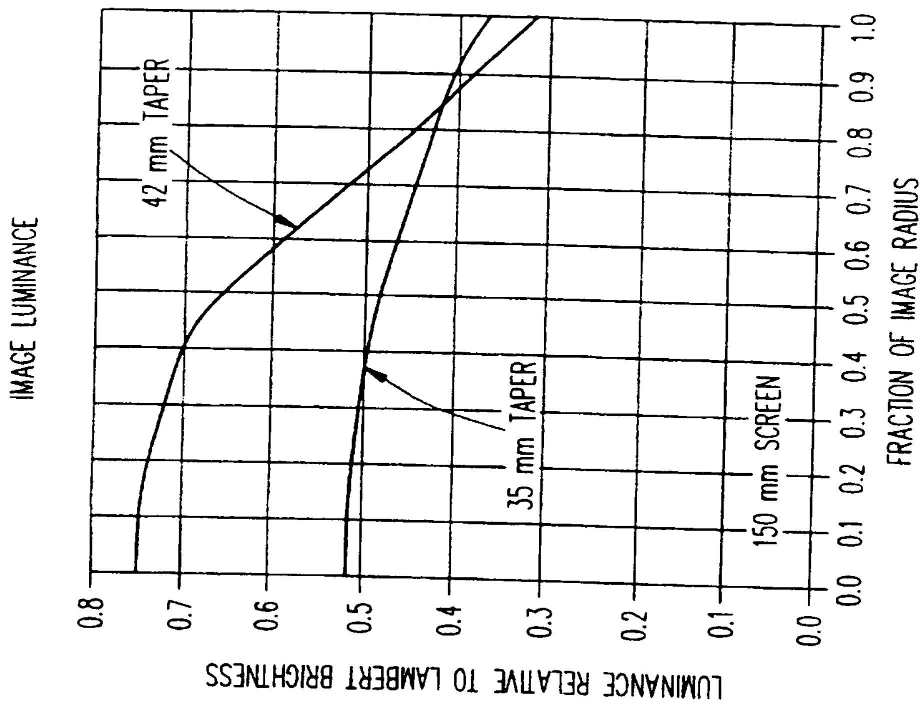
IMAGE LUMINANCE
42 mm TAPER
35 mm TAPER
150 mm SCREEN
LUMINANCE RELATIVE TO LAMBERT BRIGHTNESS
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
FRACTION OF IMAGE RADIUS
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

FIG. 8

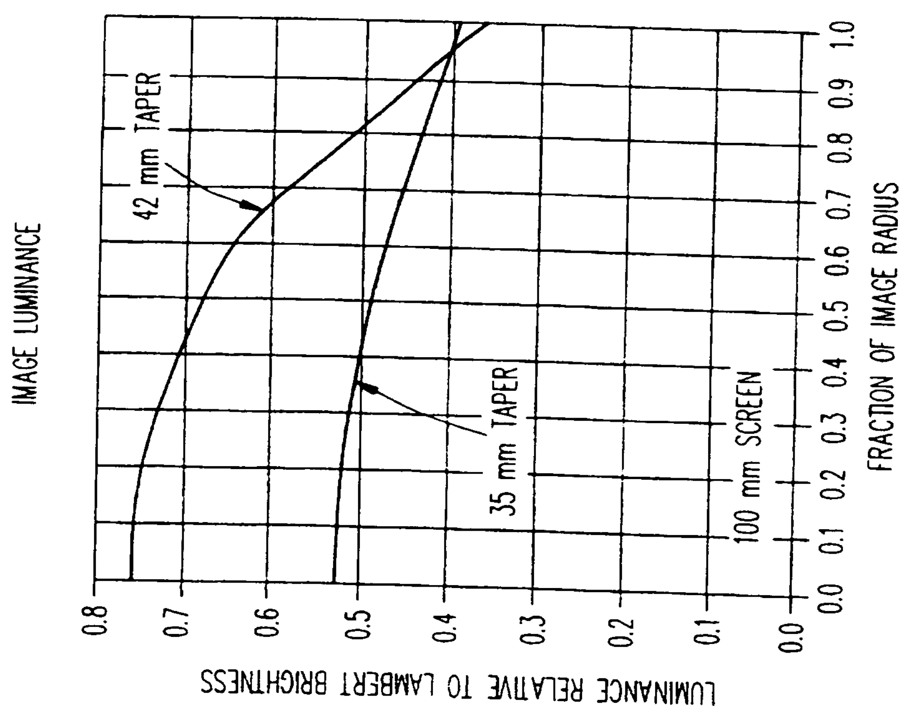
IMAGE LUMINANCE
42 mm TAPER
35 mm TAPER
100 mm SCREEN
LUMINANCE RELATIVE TO LAMBERT BRIGHTNESS
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
FRACTION OF IMAGE RADIUS
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/05669

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :GOIT 1/20
US CL :250/368,214LA
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 250/368,214LA,214VT;378/190

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X/Y	US 4,521,688 A (YIN) 04 JUNE 1985 (04/06/85), SEE FIGURE 3 AND COLUMN 5, LINES 23-29	1-24/25
Y	US 3,755,672 A (EDHOLM ET AL) 28 AUGUST 1973 (28/08/73), SEE FIGURE 1 AND ABSTRACT	25
Y	US 3,665,191 A (MOODY) 23 MAY 1972 (23/05/72), SEE FIGURE 1 AND ABSTRACT	25

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

- * Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier document published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 MAY 1997	22.05.97

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Form PCT/ISA/210 (second sheet)(July 1992)*